DEVELOPMENT OF SEMANTIC WEB – MARKUP LANGUAGES, WEB SERVICES, RULES, EXPLANATION, QUERYING, PROOF AND REASONING

Stanford University

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14. ABSTRACT
Stanford University did research, development and promotion of Semantic Web markup languages including the co-submission to the World-Wide Web Consortium (WC3) of the Web Ontology Language (OWL) recommendation. This work was performed under the Defense Advanced Research Projects Agency (DARPA) Agent Markup Language (DAML) program Stanford also helped develop the Semantic Web Services (OWL-S), the Web Ontology Query Language (OWL-QL) and Semantic Web Rule Language (SWRL) W3C submissions. This report contains the evolution of these markup languages as well as a discussion of semantic query languages, proof and explanation. The report also contains an explanation of how DAML-ONT (ontology) and DAML+OIL (Ontology Inference Language) was converted to First-Order-Logic for reasoning.

15. SUBJECT TERMS
Semantic Web, DAML, WEB Ontology Language, OWL, Semantic Web Services, Semantic Web Rule Language, SWRL, Semantic Query Languages, OWL-QL, semantic reasoning, first-order-logic

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1. Introduction

 "The Semantic Web provides a common framework that allows data to be shared and reused across applications, enterprise and community boundaries. It is a collaborative effort led by the W3C [World Wide Web Consortium] with participation from a large number of researchers and industrial partners[1]."

The Knowledge Systems Laboratory (KSL) is part of the Computer Science Department at Stanford University and has done Semantic Web research primary in the following areas during the duration this contract for the DARPA Agent Markup Language (DAML) program. The following four areas are covered in this report.

Semantic Web Markup Language Design and Development

The most significant area of Semantic Web research was on the design, development and promotion of Semantic Web markup languages. This research resulted in the development and approval by the W3C of the Web Ontology Language (OWL[2]) as a W3C recommendation[3]. OWL is a major foundation of the Semantic Web.

Web Ontology Language Semantic Web Services Markup Language design and development

A second area of research was in Semantic Web Services Markup Language design and development. This resulted in development and nomination of OWL-S the "Semantic Markup for Web Services Language" as a W3C submission[4] the step before a recommendation.

Semantically-Enabled Query Answering Environments

A third area of research was in Semantically-Enabled Query Answering Environments. This research primarily resulted in the Semantic Web Query markup languages including SPARQL a recursive name meaning "SPARQL Protocol and RDF Query Language". SPARQL has become the primary Semantic Query Language and is a W3C candidate recommendation[5].

Automating DAML-ONT (Ontology) and DAML+OIL (Ontology Inference Language) Reasoning Using a First-Order Logic Semantics

A forth major area of research was in automating the process to do reasoning using ontologies in DAML-ONT and DAML-OIL to use first-order-logic. This section describes in detail how this process was carried out in DAML research which was directly applied to the current reasoning process for the Web Ontology Language W3C recommendation.

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[1] http://www.w3.org/2001/sw/ - The definition from the Semantic Web home page on the W3C web pages.

[2] OWL was named OWL to make it more pronounceable as well as to parody the Owl character in Winnie the Pooh who spells his name Wol.

[3] essentially a nice term for a WWW standard

[4] http://www.w3.org/Submission/OWL-S/

[5] http://www.w3.org/TR/rdf-sparql-query/

We will highlight each of these areas and describe selected contributions to the Semantic Web made by Stanford University[6] in this Technical Report.

Appendix A contains a list of the 113 technical publications generated under this effort. Appendix B is a list of the professional personnel associated with this effort. Appendix C is a historical record of briefings and meetings that contributed to the current state of the Semantic Web.

2. Semantic Web Markup Language Design and Development

Stanford KSL has played a leadership role in developing, promotion and the teaching of Semantic Web representation languages. This included helping to form groups in standards organizations that either have taken a language to W3C recommendation status or are working towards a recommendation status. During the course of the program, language work has included co-authoring and/or co-submitting the following language specifications (names in parentheses include Stanford authors or editors): DAML-ONT (McGuinness), DAML+OIL (McGuinness), OWL (McGuinness), DQL/OWL-QL (Fikes, McGuinness), SWRL (McGuinness), OWL-S (McIlraith, McGuinness), and SWSF/L/O (McIlraith, McGuinness). Standards work has included helping to form and participating in the working groups or activity groups concerning ontology languages. This included helping to form and participating in ancillary groups that generated submissions to standards bodies, and participating in significant promotion and teaching activities. We will briefly mention significant group activity below in roughly chronological manner.

2.1 The DAML Language Committee (DAML-ONT working group):

This group was charged with generating an initial proposal for the ontology language for DAML. McGuinness from Stanford was one of the three editors for this effort. The resulting submission is available at: http://www.daml.org/2000/10/daml-ont.html and was released in October of 2000.

2.2 The Joint United States/European Union ad hoc Agent Markup Language Committee:

The group evolved from the DAML language committee to include international participation and broader language interest and participation. http://www.daml.org/committee/ . McGuinness was a founding member of the group and continued as a member throughout the committee history. The committee produced the DAML+OIL (Ontology Inference Layer or Ontology Interchange Layer), DQL (DAML Query Language) which later evolved into OWL-QL (OWL Query Language), and SWRL (Semantic Web Rule Language) submissions.

2.2.1 DAML+OIL

DAML+OIL (Ontology Inference Layer or Ontology Interchange Layer) was the next generation ontology language evolving from work on DAML-ONT and OIL. OIL was an ontology language of which McGuinness was one of many co-authors. McGuinness was an author of DAML+OIL and Fikes and McGuinness were co-authors of the axiomatics semantics for DAML+OIL.

An expanded set of documents was generated from this work and was submitted to W3C. McGuinness was one of six authors on the W3C note on the language reference document-

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[6] Some research was also done under this contract to develop a Semantic Web ontology for the Human Genome Project on this contract with Manchester University for DARPA. but was reported separately.

http://www.w3.org/TR/daml+oil-reference, as well as being one of six authors on the walk-through submission - http://www.w3.org/TR/daml+oil-walkthru/ . Fikes and McGuinness were the authors of the axiomatic semantics submission - http://www.w3.org/TR/daml+oil-axioms. McGuinness and Fikes were two of the six submitters of the overall package to W3C - http://www.w3.org/Submission/2001/12/. The submission of DAML+OIL was the technical impetus for the Web Ontology working group (WebOnt) so this was a significant accomplishment for the DAML program.

2.2.2 The DAML Query Language

DQL – The DAML Query Language was generated to be a query language with support for the DAML languages. Fikes was an editor of DQL and McGuinness was an author. http://www.daml.org/dql/. Stanford also generated an implementation for DQL - http://ksl.stanford.edu/projects/dql/ and subsequently generated an updated implementation for owl-ql. http://ksl.stanford.edu/projects/owl-ql/ . The final DQL release was announced in April 2003. http://www.daml.org/2003/04/dql/ As DAML evolved to OWL, the DQL query language went through updates to evolve into the OWL Query language – OWL-QL - http://ksl-web.stanford.edu/KSL_Abstracts/KSL-03-14.html

2.2.3 The Semantic Web Rule Language

 SWRL – The semantic web rule language is a language for rule representation layered on top of OWL. http://www.daml.org/rules/ . This language description was submitted to the W3C and McGuinness was one of the submitters - http://www.w3.org/Submission/2004/03/. This submission is of particular interest since it was used as one of the inputs to the W3C meeting on rule languages for interoperability- http://www.w3.org/2004/12/rules-ws/registered to gauge interest in a rules working group which McGuinness attended. The result of this work was the RIF (Rule Interchange Format) Working Group http://www.w3.org/2005/rules/ was formed. McGuinness participated in the kickoff meeting.

2.3 The W3C Web Ontology (WebOnt) Working Group:

This working group http://www.w3.org/2001/sw/WebOnt/ was formed in late 2001 http://www.w3.org/2001/sw/WebOnt/ . McGuinness helped get the group started, served as a Stanford and DAML representative, co-authored three of the major documents, and maintains them as needed. The documents include: The OWL Overview (http://www.w3.org/TR/owl-features/) for which McGuinness is the lead author; The OWL Guide (http://www.w3.org/TR/owl-guide/), and the Reference Manual(http://www.w3.org/TR/owl-ref/) . The most significant result of this working group was achieving recommendation status for the language in 2004 (http://www.w3.org/2004/01/sws-pressrelease).

Beyond being an active member in generating documents, McGuinness has given numerous briefings on OWL, the documents, and how OWL and the Semantic Web can be used. These included high visibility venues such as the National Artificial Intelligence Conference, Semantic Technologies Conference, the Joint Conference on Information Systems, and broader community venues such as the American Geophysical Union National Conference, GeoInformatics National Conference, and Information Fusion International Conference . Citations and talks are available from: http://www.ksl.stanford.edu/people/dlm/publications.html#TALKS .

Since OWL received W3C recommendation status, the increased interest increased the work oriented towards publishing it, promoting it, and educating the public about best practices in its use. As a result, the next group was formed.

2.4 The W3C Semantic Web Best Practices Working Group

W3C Semantic Web Best Practices Working Group – (http://www.w3.org/2001/sw/BestPractices/) McGuinness helped support the formation of this working group and served as the Stanford and DAML representative. She co-led the Ontology Engineering Patterns task force (http://www.w3.org/2001/sw/BestPractices/OEP/) which was concerned with providing best practice examples for ontology modeling. This group produced notes including some on representing classes as property values, specified values as value sets, n-ary relations, part-whole relations, qualified cardinality restrictions, and semantic integration.

3. DAML/OWL-Enabled Web Services

Stanford KSL played a lead role in the DAML/OWL Web Services effort. Work on this effort played key roles in the design of web services languages as well as software architecture, ontologies and tools for :
1) semantic markup of Web services that enables them to be computer-interpretable, use-apparent, and agent-ready; and
2) agent technology that exploits this semantic markup to support automated Web service discovery, execution, composition and interoperation. Specific highlights are mentioned below:

3.1 The DAML Semantic Web Services

DAML Semantic Web Services at (http://www.daml.org/services/owl-s/) . McIlraith helped form this effort and McGuinness joined later to help produce services languages and submissions to standards bodies. The group produced an initial DAML-based web service ontology (http://www.daml.org/services/daml-s/2001/05/) with McIlraith and Zeng as co-authors in May 2001. Updated versions are available from the services page. With the migration to OWL, the DAML-S effort switched to an OWL-S (Semantic Web Services based on the Web Ontology Language) effort, and the initial OWL-S version (http://www.daml.org/services/owl-s/1.0/) came out in November of 2003. Stanford's McIlraith was a key author of the language set. McGuinness later joined the group and joined McIlraith as one of the co-authors of the final version of OWL-S http://www.ai.sri.com/daml/services/owl-s/1.2/ and http://www.daml.org/services/owl-s/1.2/ which also formed the basis for the OWL-S journal paper (available as a KSL tech report: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-21.html).

3.2 The Joint United States-European Union Committee on Semantic Web Services

Joint US-EU Committee on Semantic Web Services – SWSI http://www.swsi.org/ The mission of the SWSI (Semantic Web Services Initiative) is to create infrastructure that combines semantic web and web service technologies to enable maximal automation and dynamism in all aspects of web service provision and use. There are two groups within SWSI – one being the language committee – SWSL (Semantic Web Services Language). Both McIlraith and McGuinness are members of SWSA (Semantic Web Services Architecture). One of the major accomplishments of this group was to generation the SWSF (semantic web services framework) (http://www.daml.org/services/swsf/1.0/), which included the language document (http://www.daml.org/services/swsf/1.0/swsl/), the ontology document (http://www.daml.org/services/swsf/1.0/swso/), and the applications document

(http://www.daml.org/services/swsf/1.0/applications/). Both McIlraith and McGuinness were co-authors of these documents and the full specification.   The committee generated an update to SWSF and generated a W3C submission (http://www.w3.org/Submission/SWSF/) including updates dated September 2005 to the language document (SWSL - http://www.w3.org/Submission/2005/SUBM-SWSF-SWSL-20050909/) and the ontology document -SWSO (Semantic Web Services Ontology)- http://www.w3.org/Submission/2005/SUBM-SWSF-SWSO-20050909/).   Note that this submission also includes four appendices on PSO (Process Specification Ontology) in SWSL-FOL (First Order Logic) and SWSL-Rules, an axiomatization of the FLOWS process model, an axiomatization of the process model in SWSL-Rules, and Reference Grammars all available from the SWSF submission. This submission also helped lead to the W3C workshop on frameworks for semantic web services (http://www.w3.org/2005/04/FSWS/program.html)

3.3 Designing and Prototyping Semantic Web Services Tools

During the course of the program, work was done on designing and implementing tools and prototypes to demonstrate the value and use of web services. Publications on the web services design can be found in the publication list below but a few highlights were the design and implementation of a web services editor led by McIlraith and Zeng. This was later picked up by SRI for use. Another highlight was the explainable semantic discovery service (McIlraith, Mandel, McGuinness, Pinheiro da Silva). This prototype service found service compositions in response to a request and supported explanation capabilities telling users how service compositions satisfied the response or why the service composition request failed.

4 Semantically-Enabled Query Answering Environments

Our DAML-sponsored work on query answering environments focused on explanation languages and environments, query languages and environments, and DAML- and OWL-based reasoning environments.   We will first describe highlights of the explanation work.

Our DAML-sponsored work on explaining query answering focused on designing a candidate Interlingua for representing explanations. We also designed and developed an infrastructure for utilizing the Interlingua and infrastructure in various types of applications as a testing and evolution methodology.

We gathered requirements from a broad range of applications like first order theorem provers, such as JTP – a Java-based object-oriented reasoning system, and SNARK, Stanford Research Institute's (SRI) First Order Theorem Prover. We also gathered requirements for text analytic infrastructures, such as IBM's UIMA (Unstructured Information Management Architecture), to task processing engines such as SRI's SPARK (SRI Procedural Agent Realization Kit) and web services.   We developed a set of requirements and vetted them in the general community. We also designed and implemented an infrastructure for generating, manipulating, and presenting explanations. This infrastructure is called Inference Web (http://iw.stanford.edu). We also designed and implemented the explanation interlingua – called the Proof Markup Language (PML). The Inference Web infrastructure, its components, and selected applications are all documented on the Inference Web publications page: http://iw.stanford.edu/2.0/publications.html and these listings are also included in the publications list at the end of this report.

4.1 Explanation Interlingua

We designed representational constructs necessary for encoding provenance, information manipulation, and trust information related to answers. These representational constructs were then made part of a candidate explanation and proof Interlingua language, called PML. Provenance information includes such items as information sources used in a question answering process, authors of documents, dates of generation, etc. Information manipulation information includes what reasoning steps have been done with data, what processing components have been used, etc. For example, users may need to know that text extraction components were run over natural language sources and the resulting statements were input into a reasoner to produce conclusions.

Trust information includes representations for individually and aggregated values associated with authors or components. For example, end users may need to know if algorithms such as a citation-based algorithm for determining reputation have determined a trust rating for statements. PML – the Proof Markup Language was designed to provide representational primitives for provenance, information manipulation, and trust representation. The foundational PML paper was published in 2004 and the language has gone through a revision phase so that the three individual ontologies are modular in case users need to use them separately.

PML now forms the explanation interlingua for projects including the DARPA PAL program's CALO (Cognitive Assistant that Learns and Organizes) project, the DARPA Integrated Learning GILA (Generalized Integrated Learning Architecture) project. The explanation interlingua is also being used in the National Science Foundation Cybertrust Transparent Accountable Data Mining program TAMI effort, the DTO (Disruptive Technology Office) Novel Intelligence for Massive Data (KANI) effort. The explanation interlingua is also being used in DARPA's Explainable Knowledge Aggregation effort, among others. Some of these efforts, such as CALO and GILA, include integration with a significant number of organizations – academic and industrial – as large integrated heterogeneous intelligent systems need to explain their results.

The papers writing up these results are included in the references section but to provide highlights, the best write-ups are:
DARPA PAL explanation: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-06.html
NSF Cybertrust TAMI explanation: http://www.ksl.stanford.edu/people/dlm/papers/egov-tami-abstract.html
DTO Novel Intelligence for Massive Data explanation:
http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-17.html
DARPA Explainable Knowledge Aggregation explanation:
http://www.ksl.stanford.edu/people/dlm/papers/wikitrust-abstract.html

4.2 Explanation Infrastructure:

We developed the Inference Web explanation infrastructure that supports interoperable explanations of sources, assumptions, learned information, and answers --- all as an enabler for trust. The infrastructure uses PML as its Interlingua and has components to support services for registration, search, browsing, abstraction, and trust. It has been integrated with theorem provers (JTP, SNARK, Prolog), task execution processors (SPARK), rule engines (W3C's CWM), text analytic frameworks (IBM's UIMA), and the web services modules BPEL (Business Process Execution Model) and OWL-S through the semantic discovery service.

The best overall reference for the infrastructure is: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-04-03.html

We will briefly describe the major functionality of the most important components.

1. **Registration**: A registry is provided for storing and accessing information that is used in proofs. This includes provenance information about things such as sources, authors, dates, etc. There is a set of automatic registration services that support humans and agents in generating and accessing registry contents. The best paper about this is: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-04-07.html
2. **Search**: A search service that has special knowledge of PML is available. It leverages SWOOGLE (a search capability for the Semantic Web like Google) that leverages its knowledge of RDF. In this case IWSearch (the Inference Web Search Extension) leverages SWOOGLE's knowledge of RDF and augments that with knowledge of PML to provide intelligent search services.
3. **Browsing**: Online and offline browsing services are provided that present a detailed and summarized browsing interface to PML proofs. Browsing is supported in a number of formats including limited natural language, DAG, and raw logical format. The best paper reference for the browser and search services is: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-14.html .
4. **Abstraction**: Services are available those take raw PML input and generates abstracted versions that may be more readable. The abstractor uses matching and rewrite templates to provide abstractions. It also has strategies for presenting a dialogue style interaction mode. The best paper reference is: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-06.html .
5. **Trust**: Services are available that compute trust ratings for statements based on revision- and citation-based algorithms. A trust tab presentation is available that shows how these representations may be used to present trust ratings for content. The best paper on this work is: http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-05.html

4.3 Deductive Query Answering on the Semantic Web

Our DAML-sponsored work on deductive query answering focused on developing a candidate standard formal language and protocol for a querying agent and an answering agent to use in conducting a *query-answering dialogue* on the Semantic Web. The language and protocol was first developed for use with knowledge represented in DAML+OIL and was called DAML Query Language (DQL). DQL was later upgraded to support query-answering dialogues using knowledge represented in OWL [MH03] and renamed OWL Query Language (OWL-QL). Both DQL and OWL-QL were developed collaboratively with Pat Hayes[7] and Ian Horrocks[8], and they are co-editors with us of both the DQL specification [FHH03a] and the OWL-QL specification [FHH03b].

Our work on deductive query answering was predicated on the following basic assumptions about query-answering dialogs on the Semantic Web:

The Semantic Web is expected to include many kinds of query-answering services with access to many types of information represented in many formats. Traditional database query languages like SQL

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[7] Institute for Human and Computer Cognition, University of West Florida.

[8] Information Management Group, Department of Computer Science, University of Manchester.

(Standard Query Language) [I92] and languages for retrieving information from the Web (e.g., XML (eXtensible Markup Language) query [M03] and the RDF Query Language - RQL [KC03]) are not suitable. They are unsuitable for supporting such heterogeneity, ranging from simple services that provide retrieval-based functionality, to complex services that provide sophisticated automated reasoning functionality. They also can't act as intermediary agents between their clients and more specialized servers. OWL-QL supports query-answering dialogues in which the answering agent (which we refer to as the *server*) may use automated reasoning methods to derive answers to queries, as well as scenarios in which the knowledge to be used in answering a query may be in multiple knowledge bases on the Semantic Web, and/or where those knowledge bases are not specified by the querying agent (which we refer to as the *client*).

We must expect that some servers will have only partial information about the topic, some will have performance limitations, and some will be simply unable to handle certain kinds of queries. So, it is important that the querying protocol provide some means for the transfer of partial query results and about the querying process itself. In this setting, the set of answers to a query may be of unpredictable size and may require an unpredictable amount of time to compute. OWL-QL therefore provides an adaptable query answering protocol which both allows a server to return partial sets of answers as the answers are computed and allows a client to specify the maximum number of answers that it wants the server to include in the next set of answers it sends to the client.

A Semantic Web query language needs to support queries that do not include a specification of the knowledge base(s) to be used in answering the query. That is, just as the user of a current Web browser does not specify which Web sites to consider when given a search request, we anticipate that a common use of the Semantic Web will be to send a query to a server and expect the server to select reliable knowledge sources from which to produce answers. OWL-QL supports server selection of the knowledge base(s) to be used in answering a query, and client requests that a server identify the knowledge base(s) used in answering a query.

The set of notations and surface syntactic forms used on the Web is already large, and various communities have different preferences, none of them universal. Even within the nearest to a single established syntax, XML, there are many alternative 'styles' of notational design in use. The essential aspects of the design of OWL-QL are independent of the surface syntax of the language. So, we stated the OWL-QL specification at an 'abstract' or structural level, allowing essentially the same language to be implemented in multiple surface syntactic forms. The specification describes the types of objects (e.g., queries and answers) that are passed between server and client during a query-answering dialogue, the necessary and optional components of each of those object types, and the expected response of a server to each type of object sent to it by a client. In addition, we included with the abstract specification of OWL-QL a syntax specification for the language in XML Schema in order to provide an example syntax for the language. We claim that this style of 'meta-specification' of OWL-QL will be of more utility in a Semantic Web context than the more traditional approach. For the examples in this report, we use an informal human readable surface syntax for queries and answers.

A basic premise of the Semantic Web is that the declarative languages used to represent knowledge on the Web will have a formally defined semantics and theory of logical entailment. That is the case for OWL, and for most of its predecessors, including DAML+OIL, RDF, and RDF-S. That premise also applies to query languages for the Semantic Web in that the specification of a Semantic Web query

language needs to include a formal description of the semantic relationships among a query, a query answer, and the knowledge base(s) used to produce the answer. The OWL-QL specification provides those formal descriptions.

OWL-QL is intended to be a candidate standard language and protocol for query-answering dialogues among Semantic Web computational agents during which servers may derive answers to questions posed by clients. As such, it is designed to be suitable for a broad range of query-answering services and applications. Also, although OWL-QL is specified for use with OWL, it is designed to be prototypical and easily adaptable to other declarative formal logic representation languages, including, in particular, first-order logic languages such as Knowledge Interchange Format - KIF [G98] and the earlier W3C languages, RDF [B03], RDF-S [BG03], and DAML+OIL [HHP01].

The OWL-QL Web site (http://ksl.stanford.edu/projects/owl-ql/) provides links to the OWL-QL specification and to current OWL-QL implementations, including an OWL-QL client with a Web browser user interface suitable for use by humans for asking queries of an OWL-QL server. This report describes OWL-QL and discusses significant design issues that arise in the development of a language for deductive query answering on the Semantic Web.

5 Queries and Answers

5 .1 Query Patterns and Variables

An OWL ontology K is a collection of sentences (i.e., OWL facts and OWL axioms) K_S that represents a logical theory in which a collection of entailed sentences K_{ES} are true such that $K_S \subseteq K_{ES}$. It is natural, therefore, to think of a query as asking for sentences in K_{ES} that "satisfy" a given "sentence schema", and to think of using bindings to variables in that sentence schema as specifying answers to the query. This conventional picture, which we have adopted for OWL-QL, is compatible with the semantics of the Semantic Web representation languages and is consistent with the Codd database model [C70] and many other logical formalisms.

An OWL-QL query-answering dialogue is initiated by a client sending a query to an OWL-QL server. An OWL-QL query is an object necessarily containing a *query pattern* consisting of a collection of OWL sentences (i.e., OWL facts and OWL axioms) in which some URIrefs are considered to be variables. For example, a client could ask "Who owns a red car?" with a query having the query pattern shown in Figure 1.

```
⁹Query:  ("Who owns a red car?")
Query Pattern:  {(owns ?p ?c) (type ?c Car)  (has-color ?c Red)}
Must-Bind Variables List:  (?p)
May-Bind Variables List:  ()
Don't-Bind Variables List:  ()
Answer Pattern: {(owns ?p "a red car")}
Answer KB Pattern: …
Answer:  ("Joe owns a red car?")
Answer Pattern Instance: {(owns Joe "a red car")}
Query: …
Server: …
```

Figure 1 A simple OWL-QL query and answer

A query may have zero or more answers, each of which provides bindings of URIrefs (Universal
Resource Identifier references) or literals to some of the variables in the query pattern. The bindings
provided by a query answer must be such that the conjunction[10] of the sentences produced by applying
the bindings to the query pattern. The bindings must also consider the remaining variables in the query
pattern to be existentially quantified are entailed by an OWL ontology called the *answer knowledge base*
(or simply, the *answer KB*). For example, the answer "Joe owns a red car." shown in Figure 1 means the
answer KB entails the following sentence, expressed here in first-order logic (using KIF syntax):
(exists (?c) (and (owns Joe ?c) (type ?c Car) (has-color ?c Red)))

Each binding in a query answer is a URIrefs or a literal that either explicitly occurs as a term in the
answer KB or is a term in OWL. That is, OWL-QL is designed for answering queries of the form "What
URIrefs and literals from the answer KB and OWL denote objects that make the query pattern true?" or,
when there are no variables to be bound in the query pattern, "Is the query pattern true in the answer
KB?". We will say that a variable that has a binding in a query answer is *identified* in that query answer.
The focus on entailment here is what most clearly distinguishes OWL-QL from SQL and other retrieval
languages, since although a database may be understood to entail its table entries considered as atomic
assertions and may perform simple derivations; entailment in OWL allows complex relationships to hold
which may be much more expensive to compute.

We now describe how a client specifies which syntactic elements of a query pattern are to be considered
as variables and what bindings are expected and required in a query answer. OWL has no suitable
notion of a variable, so an OWL-QL query pattern is simply a collection of OWL sentences, and a query
specifies which URI references in its query pattern are to be considered to be variables. Data base query
languages typically designate a subset of the variables in a query as being the variables for which
bindings are to be included in a query answer. In typical knowledge representation languages (including
OWL), a knowledge base (i.e., a collection of sentences in that language) may entail the existence of a
query answer but not entail a binding for every variable in the query. For example, a knowledge base
that includes sentences stating that every person has exactly one father (i.e., that every object of type

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⁹ We show a query pattern as a set of triples of the form (<property> <subject> <object>), where any item in the triple can be a variable.
   We show variables as names beginning with the character "?".

[10] We use "conjunction" informally in this introductory section since OWL does not have a logical connective for conjoining sentences or
   for conjoining knowledge bases. We consider a conjunction of sentences to be a sentence that is true if and only if all of its conjuncts are
   true.   We consider a conjunction of knowledge bases to be a knowledge base consisting of all the sentences in all the conjunct
   knowledge bases.

"Person" has exactly one value of the property "hasFather") and that Joe is a person (i.e., that "Joe" is type "Person"), entails that Joe has a father but may not entail a value of property "hasFather" for Joe. (i.e., the knowledge base may not identify the father.)

OWL-QL supports existentially quantified answers by enabling the client to designate some of the query variables for which answers will be accepted with or without bindings. That is, each variable that occurs in an OWL-QL query is considered to be a *must-bind variable*, a *may-bind variable*, or a *don't-bind variable*. Answers are required to provide bindings for all the must-bind variables, may provide bindings for any of the may-bind variables, and are not to provide bindings for any of the don't-bind variables. These designations are made by inclusion of a *must-bind variables list*, a *may-bind variables list*, and a *don't-bind variable list* in an OWL-QL query. These lists contain URI references that occur in the query, and no URI reference can be an item of more than one of these lists.

The following example illustrates the effects of having must-bind, may-bind, and don't-bind variables. Consider an answer knowledge base (KB) B containing sentences saying that every person has exactly one father, each of a large number of C_is is a person, and F_k is a father of C_k for each C_k in a small subset of the C_is. Then consider a query with the query pattern "{(hasFather ?p ?f)}", meaning "?p has father ?f", and the following cases:

If ?f is a don't-bind variable, then the complete set of query answers contains C_i answers (i.e., one for each known person), and each query answer identifies a person but does not identify the person's father.

If ?f is a must-bind variable, then the complete set of query answers contains only C_k answers (i.e., one for each known father), and each query answer identifies both a person and the person's father.

If ?f is a may-bind variable, then the complete set of non-redundant query answers contains C_i answers (i.e., one for each known person), and each query answer identifies a person and identifies the person's father in the cases where the father is known.

Specifying a query pattern and the variables lists does not indicate how the answers – the bindings to the pattern variables – are to be returned from the server to the client. OWL-QL allows a client to specify the format in which answer bindings are returned by (optionally) including an *answer pattern* in a query that can be any list expression containing all of the query's must-bind and may-bind variables. If no answer pattern is specified, a two item list whose first item is the query's must-bind variables list and whose second item is the query's may-bind variables list is used as the answer pattern. Each query answer contains an instantiation of the answer pattern in which each variable having a binding in the answer is replaced by its binding.

5.2 Including Assumptions in a Query

Since OWL does not have an "implies" logical connective, "if-then" queries such as "If Joe is a person, then does Joe have a father?" cannot be stated using only a query pattern. OWL-QL facilitates the representation of "if-then" queries by enabling a query to optionally include a *query premise* that is a collection of OWL sentences (i.e., facts and axioms). When a premise is included in a query, the sentences in the premise are considered to be included in the answer KB. Omitting the query premise is equivalent to providing an empty query premise. Figure 2 provides an example of a query that includes a premise.

```
Query:   "If C1 is a Seafood Course and W1 is a drink of C1, then what color is W1?"
Premise:  {(type C1 Seafood-Course) (has-drink W1 C1)}
Query Pattern:  {(has-color W1 ?x)}
Must-Bind Variables List:  (?x)
…
```

Figure 2 Example if-then query.

5.3 Specifying Answer Knowledge Bases

The set of OWL sentences that are used by the server in answering a query is referred to as the *answer KB*. This may be one or more actual OWL ontologies, or a virtual entity representing the total information available to the server at the time of answering. An OWL-QL query contains an *answer KB pattern* that is an OWL ontology, a URIref to an OWL ontology, a list of OWL ontologies and/or URIrefs to OWL ontologies, or a variable. If a query's answer KB pattern is an OWL ontology or a URIref to an OWL ontology, then the conjunction of the answer sentences specified by each query answer must be entailed by that ontology. If a query's answer KB pattern is a list of OWL ontologies and/or URIrefs to OWL ontologies, then the conjunction of the answer sentences specified by each query answer must be entailed by the conjunction of the ontologies in or referenced in that list. If a query's answer KB pattern is a variable, then the server is free to select or to generate an answer KB from which to answer the query, but if the variable is a must-bind variable, then the answer must provide a binding to the variable that is a URIref to an OWL ontology representing the answer KB. In many cases, that URIref will be a URL (Uniform Resource Locator) that can be used to access the ontology or to communicate with the server about the ontology, but the URIref is not required to be a URL.

5.4 Query Answering Dialogues

A query may have any number of answers, including none. In general, we cannot expect that a server will produce all the answers at once, or that the client is willing to wait for an exhaustive search to be completed by the server. We also cannot expect that all servers will guarantee to provide all answers to a query, or to not provide any redundant answers. OWL-QL attempts to provide a basic tool kit to enable clients and servers to interact under these conditions.

Answers are delivered by the server in *bundles*, and the client can specify the maximum number of answers in each bundle. Each request from a client to a server for answers to a query can include an *answer bundle size bound*, and the server is required to respond by delivering an *answer bundle* containing at most the number of query answers given by the answer bundle size bound. The collection of all answers sent to the client by the server in a query-answering dialogue is called the *response collection* of that dialogue.

An answer bundle must also contain either a *process handle* or one or more character strings called *termination tokens*. The presence of a termination token in an answer bundle indicates that the server will not deliver any more answers to the query, and the presence of a server continuation in an answer bundle represents a commitment by the server to deliver another answer bundle if more answers to the query are requested by a client.

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A client requests additional answers to a query by sending the server a *server continuation* containing the process handle provided by the server in the previously produced answer bundle and an answer bundle size bound for the next answer bundle to be produced by the server. Upon receiving a server continuation from a client, the server is expected to respond similarly by sending to that client another answer bundle. A client terminates a query-answering dialogue by sending the server a *server termination* containing the process handle provided by the server in the previously produced answer bundle. The overall structure of the dialogue is illustrated in Figure 3.
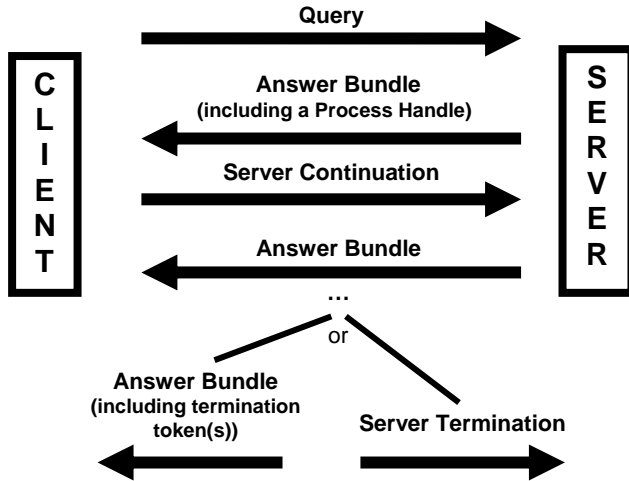
Figure 3 OWL-QL Query-Answering Dialogue.

Note that more than one client can participate in a given query-answering dialogue with a server in that the client that sends a server continuation to the server need not be the same client that sent the original query or earlier server continuations during the dialogue.

The OWL-QL specification does not restrict the nature or content of process handles. Different servers may use process handles in different ways. Some database servers may generate a complete table of answers; store it in association with a record of the query, and then use as a process handle an index or hash code keyed to the query record. Other servers may take advantage of the protocol to store enough information in a process handle to enable them to reconstruct the state of a search process and continue the search. Still others may simply store the answers already produced in a record of the query, use the query record as a process handle, and restart the query answering process from the beginning each time additional answers are requested. Note that the inclusion of a process handle in an answer bundle is not a commitment to provide more answers. If, for example, a server is unable to reconstruct the state of a query process when asked for more answers, it can always respond with an answer bundle containing a termination token and no answers.

OWL-QL specifies the following three termination tokens:
1. "**End**" simply indicates that the server is unable to deliver any more answers; it is conventionally used to terminate the process of responding to a query. One possible response to any query is a single answer bundle containing "End", indicating that the server will not provide any answers to the query.

2. "**None**" expresses an assertion by the server that no other answers are possible; i.e., that the conjunction of OWL sentences specified by any other non-redundant answer are not entailed by the answer KB.

3. "**Rejected**" can be used by a server to indicate that the query is outside its scope for some reason, e.g., by being posed in a subset of the language which it is unable to process, or by being in some way ill-formed. This is a crude device for expressing what could be a complex topic, but servers may also define their own termination tokens to be used in conjunction with the OWL-QL tokens, which can be used to express more nuanced forms of rejection.

The use of "None" would be appropriate in a case where a server has access to a collection of data which is known to be complete or exhaustive in some way, such as a database of employees of a company. Suppose a query asks for all employees with a salary over $200K, and the returned answer bundle is empty, terminated with "None". This would be sufficient grounds for the client to conclude that the company has no employees with that salary. Notice that the termination token "End" would *not* provide this kind of a guarantee, given the monotonic semantics of OWL. To treat an "End" token as though it meant "None" would be to make a 'closed-world assumption', which is not valid. The closed world assumption is the presumption that what is not currently known to be true is false. The distinction between these tokens was motivated in part by the widely noted utility of closed-world reasoning. Making the distinction explicit in the exchange protocol provides a way to express closure without forcing clients to draw invalid conclusions in cases where a closed-world assumption is inappropriate.

These conventions, taken together, allow a simple expression of a 'yes/no' query. Such queries can be expressed by a query pattern with no variables; an answer bundle containing one answer indicates that the pattern is entailed by the answer KB; an answer bundle containing no answers and the termination token "None" indicates that the query is known to not be entailed by the answer KB; and any other answer bundle containing no answers indicates that entailment of the query cannot be determined by the server.

OWL-QL does not specify a complete inter-agent protocol (e.g., with provisions for time-outs, error handling, resource budgets, etc.). OWL-QL servers are required to support the specified core protocol elements and are not constrained by the OWL-QL specification as to how additional protocol functionality is provided. Queries, answer bundles, server continuations, and server terminations are all designed to support additional protocol functionality in that they are objects consisting of property value pairs and can include values of additional properties as specified and supported by a given server.

5.5 Duplicate and Redundant Answers

While there are no global requirements on the response collection of a query answering dialogue other than that all its members are correct answers, clients will typically find it useful to know whether a given server ensures that its response collections contain no duplicate or redundant answers. Redundant answers can be a particularly vexing problem for queries whose query pattern contains a variable that is the value of maxCardinality or minCardinality for some property (i.e., an upper bound or lower bound on the number of values the property can have) since a server could potentially produce multiple and in some cases an unlimited number of answers with less and less specific bindings for such a variable. For example, if a client asks for an upper bound on the number of doors a sedan can have (i.e., the value of maxCardinality for property hasDoor in a restriction that is a superclass of class Sedan), then a server might answer with a value of 4 and then a value of 5 and then a value of 6, etc. Similarly, if a client asks

for a lower bound on the number of doors a sedan can have (i.e., the value of minCardinality for property hasDoor in a restriction that is a superclass of class Sedan), then a server might answer with a value of 2 and then a value of 1 and then a value of 0.

For some servers, assuring that no duplicate or redundant answers are produced would be very expensive, and imposing such a requirement as part of an intended standard would impose a high initial implementation cost for simple servers. On the other hand, a server that is able to deliver non-repeating or non-redundant responses may wish to advertise this useful quality. OWL-QL specifies a set of conformance levels which a server can use to do that advertising.

A server which always produces a response collection that contains no duplicate answers can be called *non-repeating*, where two answers are considered to be duplicates if they have the same set of bindings. A server which always produces a response collection that contains no redundant answers can be called *terse*, where an answer is considered to be redundant if it *subsumes* (i.e., duplicates or is less specific than) some other answer in the response set. An answer is considered to be less specific if it binds fewer may-bind variables or has less-specific bindings for variables that occur only as values of minCardinality or maxCardinality. Formally:

An answer A1 subsumes an answer A2 <u>if and only if</u>
> for every variable V that has a binding in A1's binding set,
> > V has a binding in A2's binding set <u>and</u>
> > the binding of V in A1's binding set subsumes the binding of V in A2's binding set.

For every V that occurs in a query Q,
binding B1 of a variable V subsumes a binding B2 of V <u>if and only if</u>
> B1 is identical to B2 <u>or</u>
> V occurs in Q only as a value of property minCardinality in the query pattern of Q <u>and</u>
> B1 is less than B2 <u>or</u>
> V occurs in Q only as a value of property maxCardinality in the query pattern of Q <u>and</u>
> B1 is greater than B2.

Guaranteeing terseness is a quite harsh requirement on a server that is incrementally deriving answers and returning bundles of answers as they are produced. The difficulty is that if such a server derives and returns an answer A_1 with an unbound *may-bind variable* (i.e., A_1 does not provide a binding for that variable), then it cannot later return any answer A_2 that it derives containing the same bindings as those in A_1 with the addition of a binding for the unbound *may-bind variable* because A_1 would subsume any such A_2. Similarly, if such a server derives and returns an answer A_1 with a binding B for a variable V that occurs in the query only as a value in a minCardinality (maxCardinality) restriction in the query pattern, then it cannot later return any answer A_2 that it derives containing the same bindings as those in A_1 with the addition of a binding for V that is less than (greater than) B because A_1 would subsume any such A_2.

A much more reasonable requirement is for a server to guarantee that it will not return any answer that subsumes any <u>previous</u> answer it has produced in a given query answering dialogue; that is, it will not gratuitously return answers to a client that are duplicates of or are less specific than answers it has

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already returned. Such a server can advertise itself as being *serially terse*. Note that a terse server is necessarily a serially terse server and that a serially terse server is necessarily a non-repeating server. We expect that most applications will require the OWL-QL servers they use to be serially terse.

Note that although additional criteria for answers being redundant would be useful for clients, care must be taken to consider the computational burden on a server satisfying such criteria would impose. For example, consider a variable V that occurs only as the value of an allValuesFrom restriction in a query pattern. If V has a binding to class C in a query answer, then answers which differ only in that they have a binding of V to a superclass of C would also be correct. However, those answers would be redundant and very unlikely to be useful to a client. If the definition of redundant answers were to be extended to include such variables values, a serially terse server could not return an answer containing a binding for such a variable until it determined that the subclassOf relationship is false (not just that it is unknown) between that binding and all the other bindings that it has produced for that variable in answers that differ only in their binding of that variable.

6 Discussion

6.1 Utilizing the Expressive Power of OWL

Query languages for description logics and other logic-based knowledge representation formalisms often include explicit "structural queries", such as queries asking about the subsumers, subclasses, and instances of classes [BM96] [BBH91] [BHP99]. In OWL-QL, these kinds of questions can be formulated using the standard query mechanism, taking advantage of the expressive power of the OWL language itself. For example, answers to the query using the query pattern {(subclassOf ?x Person)}, where ?x is a must-bind variable, will be the derivable subclasses of class Person. Similarly, answers to the query using the query pattern {(type ?x Person)}, where ?x is again a must-bind variable, will be the derivable instances of class Person. This ability is limited to concepts which can be expressed using OWL: for example, there is no way in OWL to express the concept of a most general subclass or a most specific type. The OWL-QL query pattern language was not extended beyond the expressive capabilities of the content language used in the knowledge bases being queried (i.e., OWL) so as not to impose greater computational burdens on a server than are defined by the specification of the language it uses.

Some SQL-style queries can be expressed using a similar technique. For example, a simple relational table might be encoded in OWL as a collection of assertions using rdf:value with the following format:

        (rdf:value ex:Joe _:x)
        (rdf:type _:x ex:employeeInfo)
        (ex:surname _:x "Jones")
        (ex:SSnumber _:x "234-55-6789")
        (ex:age _:x xsd:number^^"43")
        (ex:location _:x ex:marketing)

where the value of rdf:type is the 'table entry' and the table name is its type. The SQL command '*select SSnumber from employeeInfo*' then translates into the OWL-QL query pattern

        (rdf:type ?x ex:emplyeeInfo)
        (ex:SSnumber ?x ?y)

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with ?y being a must-bind variable and ?x being a don't bind variable. More complex SQL conditions can be expressed by more complex OWL query patterns – for example, a conditional selection can be expressed as an OWL restriction on a class such as ex:employeeInfo - but these will provide answers only if the server is able to perform the appropriate reasoning. In general, in contrast to the presumptions of the SQL querying model, the OWL-QL assumption is that nontrivial inferences about the data are performed by the server rather than by the client.

6.2 Iterative Optimization

Clients can use OWL-QL to obtain answers to queries involving concepts not expressible in OWL such as "most general subclass" or "most specific type", and indeed to optimize any variable with respect to any given transitive property, by using an iterative optimization technique as follows. To optimize the value of a must-bind variable V in a query Q with respect to a transitive property P and a server S, send Q to S asking for at most one answer. If S provides an answer to Q with a binding of B_i for V, then send S a query Q' consisting of Q with the additional premise "(P B_i V)" and ask for at most one answer. If S does not provide an answer to Q', then B_i is the optimal binding that S can provide for V. If S provides an answer to Q' with a binding of B_j for V, then send S a new query Q' consisting of Q with the additional premise "(P B_j V)". Continue this iterative querying until S does not provide an answer. The last binding produced for V is the optimal binding that S can provide for V. For example, a client could use iterative optimization to find the most general subclass of C by asking for at most one answer to a query with query pattern {(subclassOf ?x C)} and must-bind variable ?x, and then successively asking for at most one answer to the same query with the addition of premise {(subclassOf C_i ?x)}, where C_i is the most recently returned binding for ?x.

6.3 Asking About the Number of Answers

Many problems involve asking "how many" queries, such as "How many cars does Joe own?" One might be tempted to ask a "how many" query by asking an OWL-QL query and counting the number of answers produced by the server. The problems with that strategy are twofold: Firstly, the server may complete the query answering dialogue without guaranteeing that it has found all the answers; and secondly, the bindings for a given variable in multiple answers may all denote the same entity (i.e., they may be equal). So, for example, a server may respond to a query having query pattern {(type ?x car) (owns Joe ?x)} with three answers that bind ?x respectively to "Car1", "Car2", and "Car3". If the server terminates the dialogue with the termination token "End" (rather than "None"), then the client doesn't know whether the answer KB entails more bindings that denote cars owned by Joe, and the client doesn't know whether Car1=Car2, Car1=Car3, and/or Car2=Car3. So, all that the client can conclude from the server's response about how many cars Joe owns is that Joe owns at least one car. In order for the client to determine how many cars are owned by Joe, it would have to ask the query of a server that advertises itself as "complete", and it would have to make (typically multiple) subsequent queries to determine which bindings denote different cars.

The primary means that OWL provides for expressing the number of entities in a domain of discourse that satisfy some set of conditions (e.g., how many cars are owned by Joe) are cardinality restrictions on the number of values of a given property for a given individual or class of individuals (e.g., "What is the value of a cardinality restriction on property "ownsCar" for "Joe"?", where "ownsCar" is a subproperty of "owns" that has a "Car" allValuesFrom restriction of "Car" for Joe). Thus, in general, the way to meaningfully ask "how many" queries using OWL-QL is to ask for the value of an appropriate cardinality restriction, rather than asking a query and counting the answers.

OWL-QL does, in fact, allow a client to ask for how many answers a server will provide for a given query by including in the query an *answer number request* and an accompanying query variable. If the variable is a must-bind variable, then providing the number of answers is required, if the variable is a may-bind variable, then providing the number of answers is optional. The primary motivation for including this feature in OWL-QL is that many database servers record information about the number of entries in their data tables and can rapidly respond to requests for this information. Thus, such servers can often inform a client as to how many answers they will provide to a query with no significant additional effort.

7 Automating DAML-ONT and DAML+OIL Reasoning Using a First-Order Logic semantics

We developed specifications of the formal semantics of both DAML-ONT and DAML+OIL in a form that enabled existing automated reasoners to be applied to knowledge represented in those languages. It also supported the development of new more powerful automated reasoning methods for knowledge represented in those languages. We then illustrated the use of those specifications for automated reasoning by developing and incorporating into our existing JTP hybrid reasoner [FJF03] a special-purpose reasoner for knowledge represented in DAML+OIL. We made JTP with the DAML+OIL special purpose reasoner available for use as a downloadable automated reasoner (at http://ksl.stanford.edu/software/jtp/), later we upgraded the DAML+OIL special-purpose reasoner to OWL, and supported use of JTP throughout the DAML program.

To fully specify a knowledge representation language, both the syntax and the semantics of the language must be described. The syntax description specifies which strings of characters are legal statements in the language, and the semantic description specifies each legal statement's intended meaning. The semantics of a representation language can be formally specified in multiple ways. We chose to specify an equivalence-preserving translation from DAML+OIL into first-order logic (FOL). The translation consists of a mapping of DAML+OIL statements into sentences in FOL. This was accompanied by a set of FOL axioms that constrain the possible interpretations of the nonlogical symbols (that is, the relation symbols, function symbols, and constants) in the FOL sentences the mapping produced. The translation into FOL provides a semantics for DAML+OIL in that any given axiomatization of a logical theory represented in DAML+OIL is defined to be logically equivalent to an axiomatization of a theory represented in FOL, for which a declarative semantics is known.

7.1 Why First-Order-Logic?

The DAML+OIL specification submitted to W3C includes both the FOL semantics we developed and a model-theoretic semantics [H01]. The model-theoretic semantics is in the traditional form, in which an interpretation function is named for each nonlogical symbol in the language, and constraints are stated that must hold for those interpretation functions. Our work complemented the model-theoretic semantics and made the following additional contributions.

- Our translation into FOL enabled the use of traditional FOL automatic theorem provers and problem solvers to answer queries and search for logical inconsistencies in theories represented in DAML+OIL.

- Unlike standard descriptions of model-theoretic semantics, the constraints on the mappings are represented as axioms in a language for which automatic reasoning tools exist. These tools can thus be used to critique the constraints for inconsistencies and redundancies, and determine whether they entail (only) intended consequences. Tools to support such critiques are particularly important for the semantic specifications of developing languages (such as DAML+OIL), because they can help developers debug and understand the consequences of proposed language changes.

7.2 Mapping DAML+OIL to FOL

We mapped DAML+OIL to FOL using a simple rule for translating an RDF statement into a first-order relational sentence. Because DAML+OIL is simply a vocabulary of properties, classes, and constants added to RDF and RDF Schema, and RDF Schema is simply a vocabulary of properties and classes added to RDF, all statements in DAML+OIL are RDF statements. A rule for mapping RDF statements to FOL is thus sufficient for mapping DAML+OIL statements as well.

We produced a logical theory that is logically equivalent to a DAML+OIL knowledge base as follows:

1. Translate the DAML+OIL knowledge base from its concrete syntax into a collection of RDF statements.
2. Translate each RDF statement with property P, subject S, and object O into a FOL sentence of the form `(PropertyValue P S O)`, where PropertyValue denotes a ternary relation that relates a property and an entity (a subject) to a value (an object) that the property has for that entity.
3. Add the axioms that constrain the allowable interpretations of the properties, classes, and constants included in RDF, RDF Schema, and DAML+OIL.

DAML+OIL's concrete syntax is typically something other than <property, subject, object> triples. The RDF specification [LS99], for example, describes an eXtensible Markup Language encoding as the concrete syntax for RDF. Thus, the first step of the translation into FOL is a translation from a concrete syntax into RDF statements. The only requirements we impose on that translation step is that each element in the RDF statements it produces be labeled with either:

- A URI or a literal as given in the concrete syntax, or

- A Skolem constant generated by the translator for an unlabeled element in the concrete syntax (each label generated for unlabeled statement elements must be distinct).

This translation is designed to place minimal constraints on the interpretation of the nonlogical symbols in the translated logical theory and to enable the required axioms to be expressible in FOL. In particular, it does not require that properties be translated into binary relations or that classes be translated into unary relations. The translation therefore lets us state axioms that apply to all properties and all classes (that is, that use a universally quantified variable for the property or class) without quantifying over the relation in a relational sentence. Such axioms are thus expressible in FOL.

7.3 The Axiom Language

The DAML+OIL axioms were written in ANSI (American National Standards Institute) Knowledge Interchange Format (KIF) using standard FOL constructs and KIF-specific relations and functions for integers that were used to axiomatize the DAML+OIL properties dealing with cardinality.

As we stated earlier, we translated the RDF statement, "Property P of resource R has value V" into the KIF sentence, `(PropertyValue P R V)`. Because the type property is central in RDF, we defined an additional binary relation called `Type` to provide a more succinct translation of RDF statements of the form, "Property 'type' of resource R has value V". The meaning of the `Type` relation is specified by the following axiom:

(<=> (Type ?r ?v) (PropertyValue type ?r ?v)).

In KIF, "`<=>`" means "if and only if," relational sentences have the form "`(<relation name> <argument>*)`", and names with the first character "?" are variables. Also, if no explicit quantifier is specified, variables are assumed to be universally quantified. So, the axiom above says that for all objects R and V, relation Type holds for R and V if and only if relation PropertyValue holds for object type, R, and V.

7.4 RDF Axioms

Because DAML+OIL is specified as an extension to the RDF and RDF Schema vocabulary, our axiomatization included axioms describing the properties and classes in both RDF and RDF Schema, as well as those in DAML+OIL itself. RDF is a language for:

- Declaring named resources to have type `Property` or `Class`,
- Declaring resources to have a given class as a type; e.g., Clyde is type Elephant
- Stating that a given property of a given resource has a given value; e.g., the property Color of Clyde has value Gray.

The type property is used in RDF for declaring that the type of some resource R is some class T; such a declaration is actually a statement that property type of resource R has value T. Thus, an RDF knowledge base consists entirely of statements of the form, "Property P of resource R has value V".

The axiomatization provides axioms restricting the interpretation of the classes and properties in the RDF Schema vocabulary. The axioms include constraints, such as that the first argument of relation `PropertyValue` must be a property; that an entity cannot have both `Property` and `Class` as types (that is, they are disjoint classes); and that an RDF statement has exactly one property, one object, and one subject.

7.5 RDF Schema Axioms

RDF Schema is simply a vocabulary of properties and classes added to RDF, and the axiomatization restricts the possible interpretations of those classes and properties. The added vocabulary includes standard properties such as `subClassOf, subPropertyOf, range`, and `domain`. The axioms include constraints, such as: a `superClass` of an object type is also a type of that object; if an entity is a value of another property's `subClass`, then the entity is also a value of the other property; a property value must have the range of that property as a type; and that an object that has a value for a property must have that property's domain as a type.

7.6 DAML+OIL Axioms

DAML+OIL is simply a vocabulary of properties and classes added to RDF and RDF Schema. The DAML+OIL axioms are significantly more extensive than the axioms for either RDF or RDF Schema. They include constraints that:

- Add 12 classes to the subclass taxonomy and 26 properties to the subproperty taxonomy.

- Specify domain and range constraints for each of the new classes and properties

- Define the class of all objects as (Thing), the empty class as (Nothing), the class of properties that are transitive, the class of properties that can have at most one value for a given object (UniqueProperty), the class of properties that can have a given value for at most one object (UnambiguousProperty), the property for stating that classes are disjoint (disjointWith), the property for stating that properties are inverses of each other (inverseOf), and a property for stating that classes are complements of each other (complementOf).

- Defines properties for stating the equivalence of objects, classes, or properties

- Define properties for stating that a class is a union, intersection, or disjoint intersection of a list of classes.

- Defines the various kinds of cardinality and value restrictions.

- Defines lists and their properties.

One of the challenges in writing the DAML+OIL axioms was axiomatizing the various cardinality restrictions that are expressible in the language (minCardinality, maxCardinalityQ, and so on) without adding a set theory to FOL. We dealt with this issue by writing a simple axiomatization of tuples and their length, and then defined a type of tuple that has no repeating elements. In those axioms, we defined the empty tuple, EmptyTuple; the binary relation, Item, which relates a tuple to each of its elements; the unary function, First, which maps a nonempty tuple to its first element; the unary function, Rest, which maps a nonempty tuple to the tuple consisting of its second through last elements; the unary function, Length, which maps a tuple to the number of elements it has; and the unary relation, NoRepeatsTuple, which is true of tuples that have no repeating elements. The axiom that defines the NoRepeatsTuple relation is:

```
(<=>   (NoRepeatsTuple      ?t)
       (and    (Type   ?t   Tuple)
               (or     (=     ?t    EmptyTuple)
                       (=   (Rest    ?t)        EmptyTuple)
                       (and    (not   (Item   (Rest    ?t)   (First   ?t)))
                       (NoRepeatsTuple    Rest    ?t)))))
```

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Given this axiomatization, we wrote axioms for each of the cardinality restrictions. As an example, the following axiom for `cardinality` expresses a constraint on the `NoRepeatsTuple` length that it contains all of a given property's values at any one object:

```
(=>    (and    (PropertyValue  onProperty  ?r  ?p)
               (PropertyValue  cardinality  ?r  ?n))
       (forall  (?i)
               (<=>   (Type  ?i  ?r)
                      (exists  (?vl)
                              (and    (NoRepeatsTuple  ?vl)
                                       (forall   (?v)
                                              (<=>  (Item  ?vl  ?v)
                                                    (PropertyValue  ?p  ?i  ?v)))
                              (= (Length ?v1) ?n)))))))
```

7.7 Example Translation and Inference

Consider the following DAML+OIL descriptions of class "Wine" and of wine "MyFavoriteDrink":

```
<daml:Class rdf:ID = "Wine">
       <rdfs:subClassOf rdf:resource = "Drink"/>
       <rdfs:subClassOf>
              <daml:Restriction>
                     <daml:onProperty rdf:resource = "hasWineColor"/>
                     <daml:toClass rdf:resource = "WineColor"/>
              </daml:Restriction>
       </rdfs:subClassOf>
</daml:Class>
<Wine rdf:ID = "MyFavoriteDrink">
       <has WineColor rdf:resource = "Red"/>
</Wine>
<rdfs:subClassOf rdf:resource = "Drink"/>
       <rdfs:subClassOf>
              <daml:Restriction>
                     <daml:onProperty rdf:resource = "hasWineColor"/>
                     <daml:toClass rdf:resource = "WineColor"/>
              </daml:Restriction>
</rdfs:subClassOf>
</daml:Class>
<Wine rdf:ID = "MyFavoriteDrink">
       <has WineColor rdf:resource = "Red"/>
</Wine>
```

Those descriptions are equivalent to the following RDF statements:
     (rdf:type Wine daml:Class)
     (rdfs:subClassOf Wine Drink)
     (rdfs:subClassOf Wine GnR) ["GnR" is the generated label for the

<center>unlabeled restriction.]</center>

      (rdf:type GnR daml:Restriction)
      (daml:onProperty GnR has WineColor)
      (daml:toClass GnR WineColor)
      (rdf:type MyFavoriteDrink Wine)
      (hasWineColor MyFavoriteDrink Red)

Our FOL semantics translate those RDF statements into the following FOL sentences:

      (Type Wine daml:Class)
      (PropertyValue rdfs:subClassOf Wine Drink)
      (Type GnR daml:Restriction)
      (PropertyValue rdfs:subClassOf Wine GnR)
      (PropertyValue daml:onProperty GnR hasWineColor)
      (PropertyValue daml:toClass GnR WineColor)
          (Type MyFavoriateDrink Wine)
      (PropertyValue has WineColor MyFavoriteDrink Red)

An FOL reasoner can infer from these sentences and the DAML+OIL axioms that `Red` is type `WineColor`. It makes that inference by first inferring that `Red` is type `GnR,` using the following `subClassOf` axiom:

      (<=> (PropertyValue subClassOf ?csub ?csuper)
          (and (Type ?csub rdfs:Class)
               (Type ?csuper rdfs:Class)
               (forall (?x) (=> (Type ?x ?csub) (Type ?x ?csuper))))))

If the reasoner substitutes `Wine` for `?csub` and `GnR` for `?csuper`, the axiom can be used to infer the following:

      (=> (PropertyValue subClassOf Wine GnR)
          (=> (Type MyFavoriteDrink Wine) (Type MyFavoriteDrink GnR)))

Because `(PropertyValue subClassOf Wine GnR)` and `(Type MyFavoriteDrink Wine)` are given, the reasoner can infer `(Type MyFavoriteDrink GnR)`. It can then infer that `Red` is type `WineColor` using the axiom:

      (=>   (and (PropertyValue onProperty ?r ?p)
               (PropertyValue toClass ?r ?c))
          (forall (?i) (<=> (Type ?i ?r)
                      (forall (?j) (=> (PropertyValue ?p ?i ?j)
                                 (Type ?j ?c))))))

The axiom says that if `R` is a `toClass` restriction on class `C` for property `P`, then for all `I`, `I` is type `R` if and only if all values `J` of `P` are type `C`. If the reasoner substitutes `GnR` for `?r`, `hasWineColor` for `?p`, `WineColor` for `?c`, and `MyFavoriteDrink` for `?i`, the axiom can be used to infer:

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```
(=>     (PropertyValue hasWineColor MyFavoriteDrink ?j)
        (Type ?j WineColor))
```

If the reasoner substitutes `Red` for `?j` in that intermediate result, it can infer `(Type Red WineColor)`, which is what we set out to prove.

7.8 Theorems for Automatic Reasoning

A primary motivation for developing a translation of DAML+OIL into FOL was to facilitate automatic query-answering — that is, a deductive retrieval of objects that match a given set of constraints — from a DAML+OIL knowledge base. It would be difficult for a reasoner to use many of the axioms as written. We therefore produced a set of theorems that are inferable from the axioms for RDF, RDF-Schema, and DAML+OIL, and that are in the Horn Clause form that is conducive to effective FOL theorem prover use. (A Horn Clause is an implication of the form `(=> (and a1 … an) c)`, where each of `a1, …, an`, and `c` are atomic sentences. In this case, an atomic sentence is either an RDF statement or false.)

The theorems (which are in [FM00]) should state all of the RDF statements that can be inferred about the knowledge base's vocabulary — that is, about constants that are either explicitly mentioned in the knowledge base or defined in the knowledge base language (RDF, RDF-Schema, or DAML+OIL). So, for example, the theorems express a consequence that a given object is an instance of the complement of a given class only if the complement of that class is already a named class in the knowledge base.

The theorems can be considered as the "intended consequences" of the axioms expressed in forms that traditional FOL reasoners can directly use. Any intended consequence of the axioms that a FOL reasoner is having difficulty making can be expressed as a Horn Clause, which a theorem prover can attempt to prove from the axioms. If the proof succeeds, then the Horn Clause is a theorem that a FOL reasoner can use directly in future reasoning to infer the intended consequence.

The most important theorems in terms of facilitating reasoning are those involving the various cardinality restrictions. The axioms that define the semantics of cardinality restrictions using a `NoRepeatsTuple` are difficult for FOL reasoners to use effectively. For example, such reasoners would have difficulty using them to make standard inferences about inconsistent cardinality restrictions (such as when a `maxCardinality` restriction is less than a corresponding `minCardinality` restriction) and equality of property values (such as when there are two values of a property for an object that has a `maxCardinality` restriction of 1). The theorems support each of those standard inferences by providing a Horn Clause that a reasoner can use to directly make the desired conclusion.

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APPENDIX A – Technical Publications

The following is a cumulative chronological list of technical publications from this effort.

- David Martin, Mark Burstein, Drew McDermott, Deborah L. McGuinness, Sheila McIlraith, Massimo Paolucci, Evren Sirin, Naveen Srinivasan, and Katia Sycara. Bringing Semantics to Web Services with OWL-S. World Wide Web Journal, to appear. Also, Stanford KSL Technical Report KSL-06-21 http://www.ksl.stanford.edu/KSL_Abstracts/KSL-06-21.html

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- Sheila McIlraith and Richard Scherl; ``What Sensing Tells Us: Towards a Formal Theory of Testing for Dynamical Systems''; Proceedings of the Seventeenth National Conference on Artificial Intelligence (AAAI2000); pp. 483-490; Austin, Texas July 30 - August 3, 2000. Available from: http://www.ksl.stanford.edu/people/sam/aaai00.ps

- Sheila McIlraith; ``Modeling and Programming Devices and Web Agents''; Proceedings of the NASA Goddard Workshop on Formal Approaches to Agent-Based Systems; Lecture Notes in Computer Science; Springer-Verlag; to appear, 2000. Available from: http://www.ksl.stanford.edu/people/sam/nasa00.ps

APPENDIX B Professional personnel associated with this research effort

Richard Fikes – co-PI
Professor (Research) Emeritus Computer Science (and
previous co-Director of KSL)
Ph.D. (Computer Science), Carnegie-Mellon University.
Thesis title: "REF-ARF: A System for Solving Problems Stated as Procedures".
M.A. (Mathematics), University of Texas at Austin.

Deborah McGuinness – Technical Program Manager and co-Investigator
Acting Director KSL and Senior Research Scientist
Ph.D. (Computer Science), Rutgers University.
Thesis title: "Explaining Reasoning in Description Logics".
M.S. (Computer Science and Electrical Engineering), University of California at Berkeley.
Thesis title: "An Inferencing Language for Relational Geometric Databases".

Li Ding – Post Doctoral Fellow
Ph.D. (Computer Science) University of Maryland Baltimore County
M. S. (Computer Science) Peking University
B.S. (Computer Science) Peking University

Sheila McIlraith – Previous Technical Lead – Web Services
Consulting Professor (and Assistant Professor University of Toronto)
Ph.D. (Computer Science), University of Toronto
Thesis: "Towards a Formal Account of Diagnostic Problem Solving"
M. Math (Computer Science), University of Waterloo

Paulo Pinheiro da Silva – Previous Post Doctoral Fellow
Ph. D. (Computer Science) University of Manchester
M. Sc. (Computer Science) Universidade Federal de Minas Gerais, Belo Horizonte, Brazil.

Cynthia Chang – Programming Staff

Honglei Zeng – Student

Dhyanesh Narayan – Previous Student

Dan Mandell – Previous Student

Jessica Jenkins – Previous Programming Staff/Student

Rob McCool – Previous Programming Staff

Priyendra Deshwal - Previous Student

APPENDIX C Cumulative presentations at meetings, conferences, seminars, etc.

Because of the significance of the W3C recommendations and contributions to the Semantic Web Vision these meetings are included with slides and documentation where available

January 16, 2007. Deborah L. McGuinness. *Emerging Trends in Web Research: Transparent, Trustworthy Applications and Semantically-Enabled Scientific Data Integration*. Invited talk for the Duke Information Science and Information Studies Lecture Series, Duke University, Durham, NC.

January 12, 2007. Deborah L. McGuinness. *Trends in Semantic Web Research*. Invited talk. University of Central Florida, Orlando, Florida.

November 6, 2006. Deborah L. McGuinness. *GeoSpatial Ontologies*. Invited talk for the Terra Cognita - Directions to the Geospatial Semantic Web Workshop, in conjunction with the International Semantic Web Conference, Athens, Georgia, November 6, 2006.

October 25-27, 2006. Deborah L. McGuinness. *Information Integration Issues in Scientific Applications*. Invited talk for the NSF Workshop on Information Integration. University of Pennsylvania, Philadelphia, Pennsylvania, slides, paper.

October 16-19, 2006. Deborah L. McGuinness. *Semantic Web Progress and Directions*. Invited talk for Object Modeling Group Service Oriented Architecture Meeting. Burlingame, Ca..

June 28-29, 2006. Deborah L. McGuinness. *Explanation infrastructure supporting transparency and accountability*. Invited talk for the TAMI/Portia Workshop on Privacy and Accountabilty, MIT, Cambridge, Mass.

May 11-12, 2006. Deborah L. McGuinness. *Solar Terrestrial Ontologies*. Invited talk for the GeoInformatics conference, Reston, Virginia.

April 26, 2006. Deborah L. McGuinness. *Two Emerging Trends in the Semantic Web: Trust and Semantic Integration of Scientific Data*. Invited talk for the Norwegian Semantic Days, Stavanger, Norway, Extended version of the talk repeated at University of Trondheim, April 28, 2006

March 26, 2006. Deborah L. McGuinness.The Future of the Knowledge Principle and Knowledge Systems. Ed Feigenbaum's Festschrift. Stanford University, Stanford, CA.

March 30, 2006. Deborah L. McGuinness. New Directions for the Semantic Web. Object Management Group (OMG) Service-Oriented Architecture, Meta Data Architecture, and Web Services Workshop: Integrating the Enterprise, and Beyond, Fairfax, Va.

March 8, 2006. Deborah L. McGuinness. *Making Web Applications Trustable*. Keynote Address for the Semantic Technology Conference. San Jose, California, March 8, 2006. abstract.

January 18, 2005. Deborah L. McGuinness presents proof and trust for intelligence applications. Intelligence Community closed meeting Annapolis Junction, MD.

December 8, 2005. Deborah L. McGuinness. Ontologies and the Semantic Web: Key Enablers for Earth and Space Science Advances. Invited talk for the American Geophysical Union AGU Fall Meeting Earth and Space Science Informatics Session, Moscone Center, San Francisco, CA. abstract.

November 5, 2005. Paulo Pinheiro da Silva, Honglei Zeng, Deborah L. McGuinness, and Richard Fikes. Towards Explainable Systems. Invited talk at *International Symposium on Explanation-aware Computing*, AAAI Fall Symposium, Washington, D.C.

August 5, 2005. Deborah L. McGuinness. *The Future of Proof and Trust on the Web*. Invited talk for Pacific Northwest National Lab Symposium. Richland, Wa.

July 23, 2005. Deborah L. McGuinness. *Why Should You Trust Answers from the Web*. Invited talk for the Joint Conference on Information Sciences, Web Intelligence and Security Track, Salt Lake City, Utah. A paper accompanies this talk.

June 11, 2005. Deborah L. McGuinness. *The Semantic Web and Digital Libraries as Knowledge Systems*. Invited talk for Digital Libraries: Cyberinfrastructure for Research and Education (JCDL2005). International Scientific Data, Standards, and Digital Libraries Track. Denver, Colorado, June 11, 2005.

June 9, 2005. S. McIraith. SWSF Ontology (FLOWS). W3C workshop on Frameworks for Semantics in Web Services, Innsbruck, Austria. June 9. 2005.

May 25, 2005. Deborah L. McGuinness. *Semantically-Enabled Explanations of Text Analysis Results*. Invited talk for the Department of Homeland Security Advanced Scientific Computing Program Text Analysis Workshop, Alexandria, Virginia, May 25, 2005.

April 7, 2005. Deborah L. McGuinness. *The Substance of the Semantic Web*. Invited talk for the Semantic Web Applications for National Security. Washington, DC, April 7, 2005.

March 24, 2005. Deborah L. McGuinness. *The Semantic Web: Infrastructure for the Next Generation Web Applications and Services*. Invited talk for the Object Modeling Group (OMG) Meeting on Model Driven Architecture and Web Services. agenda. Orlando, Florida, March 24, 2005.

March 3-4, 2005. Deborah L. McGuinness. *Ontologies and Ontological Engineering*. Invited talk for NSF Geo-Ontology Workshop. San Diego Super Computer Center, San Diego, Ca., March 3-4, 2005.

Feb 22-23, 2005. Deborah L. McGuinness. *Explaining Results*. Invited Talk for Sierra Nevada Corporation's Technical Exchange Meeting, San Antonio, Texas, February 22-23, 2005.

February 17, 2005. Deborah L. McGuinness. *Explainable Semantic Discovery Services.* Stanford Networking Research Center Symposium. Stanford, Ca., February 17, 2005. talk.

June 17-18, 2004. Deborah McGuinness presents Inference Web at the DARPA/ IBM UIMA text analytics meeting. Palisades, New York. Fikes also attended from KSL.

June 16, 2004; Richard Fikes gave the presentation "Semantic Integration: Assuring the Coherence of Integrated Information" at the Rome Air Development Center in Rome, New York.

June 15, 2004. Deborah McGuinness briefs Paul Allen and Vulcan Ventures on the Semantic Web. Seattle, Washington.

June 6, 2004. Sheila McIlraith. *Towards Semantic Web Services: OWL-S and Web Service Composition.* Invited Speaker at the 2004 International Workshop on Description Logics (DL2004). Whistler, British Columbia, Canada.

May 25-26. McGuinness and Pinheiro da Silva attend the DAML PI Meeting. McGuinness presents KSL work on speaking schedule and McGuinness and Pinheiro da Silva present demos including work from KSL from Chang, Fikes, Jenkins, Mandell, McCool, and McIlraith.

May 24. McGuinness attends Face to Face meeting for the Semantic Web Services Initiative. New York, New York.

May 18, 2004. Deborah McGuinness. Explanation as a way of increasing Trust. DARPA BioOntologies meeting. SRI, Menlo Park, CA

April 27-28, 2004. Deborah McGuinness and Sheila McIlraith participate in the DARPA Self Awareness Workshop. SRI International, Arlington, VA.

April 21, 2004. Deborah McGuinness. The Future of the Semantic Web. Keynote talk for the SDForum Semantic Technologies Seminar. PARC – George E. Pake Auditorium, Palo Alto, CA. (http://www.sdforum.org/SDForum/Templates/CalendarEvent.aspx?CID=1374&mo=4&yr=2004)

March 1, 2004. Deborah McGuinness. *Ontologies and the Semantic Web.* Invited talk for Genentech's Corporate Information Technology Symposium, Burlingame, CA..

November 12, 2003. Richard Fikes. Knowledge Representation and Reasoning; invited lecture given at the Cognitive Systems Conference celebrating the 40th anniversary of the DARPA Information Processing Technology Office (IPTO); Arlington, VA;

November 7, 2003; Fikes gave the invited talk "Semantic Integration: Assuring the Coherence of Integrated Information" at the IBM-Stanford Day; Stanford University.

October 2003. Mandell and McIlraith present OWL-S +BPEL4WS paper at ISWC2003.

October 2003. McGuinness and Pinheiro da Silva present Inference Web paper at ISWC2003.

October 2003. McGuinness and McIlraith attended SWSL face-to-face.

September 30, 2003: Deborah McGuinness presented *Explanation: The Next Phase in Question Answering Systems.* In the Distinguished Lecture Series, Berkeley Initiatives in Soft Computing, September 30, 2003.

July 29, 2003; Fikes presented the paper "JTP: A System Architecture and Component Library for Hybrid Reasoning" at the 7th World Multiconference on Systemics, Cybernetics, and Informatics (SCI-2003) in Orlando, Florida.

July 9, 2003: Deborah McGuinness presented: *Ontologies for Information Fusion*. Invited talk for Information Fusion 2003, Cairns Australia, July 9, 2003.

April 30, 2003. McGuinness presented The State of the Semantic Web to the Norwegian Trade Consulate.

April 29, 2003. McGuinness briefed W3C on Inference web and evaluated the use of Inference Web in W3C efforts.

April 16, 2003. McGuinness presented Inference Web to ARDA visitors along with CIA, NSA, DIA. Fikes briefed JTP and DQL.

April 10, 2003; Fikes gave the DAML Query Breakout Session Outbrief at the DAML Principal Investigators Meeting in Miami, FL.

April 9, 2003; Fikes gave the presentation "DAML Query Language (DQL)" in the DAML Query Breakout Session at the DAML Principal Investigators Meeting in Miami, FL.

April 7, 2003; Fikes gave the presentation "DAML Query Language (DQL) Overview" at the DAML Principal Investigators Meeting in Miami, FL.

March 2003. McGuinness presents invited keynote *Knowledge Representation for Question Answering*. Invited talk for New Directions in Question Answering American Association for Artificial Intelligence Spring Symposium Series. Stanford, CA March, 2003.

March 2003. McGuinness attended the editors meeting of WebOnt at the W3C meeting remotely and presented the state of the OWL Guide and her portion of the OWL Guide and tutorial.

February 20, 2003. McGuinness briefed the Biological Pathways group on OWL at SRI.

January 9-10, McGuinness attended the WebOnt Face to Face meeting remotely and presented the state of the OWL Overview.

November 2002. McGuinness presents Keynote Address on the Semantic Web and Electronic Health at the Ehealth meeting.

October 2002. McIlraith gave talk at Sony Research Labs on DAML-enabled Web Services.

October 2002. McGuinness represents Stanford and DAML at W3C Webont meeting in Manchester and presents OWL guide ontology.

October 2002. McGuinness presents Stanford KSL wine agent at DAML PI meeting and presents explanation at PI meeting.

September 25, 2002 McIlraith gave keynote at International Conference on Automated Software Engineering (ASE2002) on Semantic Web Services.

September 6, 2002. McGuinness met with Sentius Corporation about their potential corporate use of DAML and possible integration into products.

August 5, 2002. McGuinness met with Rockmore, McCune (Cyladian) and Bizgent about potential DAML spinout applications.

July 29, 2002; Fikes gave the presentation "A Reusable Time Ontology" at the Ontologies for the Semantic Web workshop at the AAAI 2002 National Conference in Edmonton, Alberta.

July 29, 2002; Fikes gave the keynote address "Ontologies and The Semantic Web" at the Ontologies for the Semantic Web workshop at the AAAI 2002 National Conference in Edmonton, Alberta.

July 2002, McGuinness attends executive council meeting for AAAI.

July 2002, McGuinness gave keynote address at AAAI meeting on Semantic Web meets Language Resources workshop.

July 2002 McGuinness hosted WebOnt meeting at Stanford University and generated OWL Lite Overview specification document.

May 2002, McIlraith reported on DAML-Enabled Web Services at Stanford Formal Reasoning Group meeting.

June 2002 McIlraith (with Fensel) gave tutorial on Semantic Web Services at XML One/Web Services One Conference, San Jose, CA.

May, June 2002 invited talks by McIlraith on "Automated Web Service Composition" at University of Toronto and University of British Columbia.

May 27 2002 invited talk by McIlraith on "Web Services Meet the Semantic Web" at the Fourth International Bi-conference Workshop on Agent-Oriented Information Systems.

April, May, June 2002 McIlraith and Fikes met w/ Fortune 500 company to discuss collaborative work.

April 2002. McGuinness was program chair of the international knowledge representation and reasoning conference. She ran a meeting on OWL Lite and co-generated a proposal and readout of the meeting.

April 2002. KR2002 McIlraith presented joint paper with Tran Cao Son on DAML-enabled Web service composition.

April 2002 NMR2002 McIlraith presented joint paper with Ron Fadel on planning for Web service composition.

April 2002 AIPS 2002 McIlraith presented joint paper with Tran Cao Son on DAML-enabled Web service composition.

March 26, 2002. invited talk by McIlraith on Synthesizing Web Services on the Semantic Web at American Association for Artificial Intelligence Spring Symposium on Logic-Based Program Synthesis: State of the Art and Future Trends.

March 26, 2002. McGuinness reported on Explanation for Query Answering. American Association for Artificial Intelligence Spring Symposium Series Meeting on Mining Answers from Texts and Knowledge Bases.

February 28, 2002 McGuinness reported on explanations of reasoning for rapid knowledge formation that utilized DAML foundation.

February 12-14, 2002 DAML PI Meeting: http://www.daml.org/meetings/2002/02/pi/agenda.html

McGuinness provided a readout on the W3C Web Ontology Working group status and recent meetings. Fikes presented KSL's work on the JTP reasoner. McIlraith was unable to attend at the last minute.

Feb 8, 2002. Ontologies and the Web. McGuinness gave invited talk at the Intel Semantic Web day, Hillsborough, Ore.

February 2002, McIlraith gave presentation on DAML-S at Ultralog meeting in Boston.

February 2002, McIlraith gave presentation on DAML-S at IXO study panel in LA.

October 2001. McIlraith gave talk on DAML-S, BPEL4WS at Sony Research Labs, San Jose.

October 2001 McIlraith participated in Expert Panel on Web Services, XML One/Web Services One Conference, San Jose, CA., October, 2001. ``The Future of Web Services and Implications for Web Service Developers.''

September, 2001. McIlraith gave invited lecture at Stanford Networking Research Meeting. Topic: DAML-S and Services on the Semantic Web.

August 2001. McGuinness gave presentation on the Future of The Semantic Web. *International Conference on Conceptual Structures*, Stanford, Ca.,

   - August, 2001. McIlraith gave presentation at the Workshop on Nonmonotonic Reasoning, Action and Change, '', International Joint Conference on Artificial Intelligence (IJCAI'01), Seattle, WA. Paper: "Adapting Golog for Programming the Semantic Web"

August, 2001. McIlraith participated in the IJCAI "Semantic Web Panel", International Joint Conference on Artificial Intelligence (IJCAI'01), Seattle, WA.   Topic of Panel: ``The Semantic Web Elephant. What the Blind Men See."

August 1, 2001. McGuinness presented a talk on Description Logics Emerge from Ivory Towers in the joint session of the International Description Logic Workshop and the International Conference on Conceptual Structures.

August 1, 2001: McIlraith gave presentation at Int. Semantic Web Working Symposium (SWWS). Topic: ``Web Applications and Web Services – Facilitators Report''

July 31, 2001. McGuinness presented of the Future of the Semantic Web on an invited panel for the International Conference on Conceptual Structures.

August 1, 2001. McGuinness and Tuttle presented the Facilitators Report on the Ontology Track of the International Semantic Web Working Symposium.

July, 2001. McIlraith gave invited presentation at European IBROW Meeting, Stanford, CA. Topic: ``DAML-S and Services on the Semantic Web."

July, 2001. McIlraith gave invited tutorial and presentation at Cisco Systems, Mountainview, CA. Topic: ``DAML-S and Services on the Semantic Web."

July 18-20, 2001. DAML PI Meeting.
Presentation by McIlraith on behalf of DAML-S Coalition: "DAML-S Briefing"
Presentation by Fikes and McIlraith on "What's Hot and What's Happening" at KSL.
Demonstration by McGuinness on KSL ontology tools – Chimaera (with Ontolingua).
Fikes organized and chaired a breakout session on the design of a query-answering language for DAML and provided an outbriefing of the session later.

July 17, 2001. McGuinness gave lecture at EU/US Joint Committee on Markup Language meeting prior to DAML PI meeting.

June 19, 2001. McIlraith gave invited lecture at Xerox Palo Alto Research Center (PARC), Palo Alto. Topic: DAML-Enabled Semantic Web Services and Web Service Composition.

June 13, 2001. McGuinness gave invited lecture at Nokia Research Headquarters on The Semantic Web. Helsinki, Finland.

June 12, 2001. McGuinness gave keynote address at the IEEE International communications Conference, Helsinki, Finland.   Title: "The Future of the Web".

June 7, 2001. McIlraith gave invited lecture at University of Linkoping, Linkoping. Sweden. Topic: DAML-Enabled Semantic Web Services and Web Service Composition.

May 31, 2001. McIlraith gave invited lecture at National Research Council, Ottawa, Canada. Topic: Topic: DAML-Enabled Semantic Web Services and Web Service Composition.

May 29, 2001. McIlraith gave invited talk at Workshop on Ontologies in Agent Systems, 5th International Conference on Autonomous Agents. Topic: DAML-Enabled Semantic Web Services and Web Service Composition.

May, 2001. McIlraith gave presentation at the Fifth Symposium on Logical Formalizations of Commonsense Reasoning (Common Sense 2001). Paper: "Adapting Golog for Programming the Semantic Web"

May, 2001. McIlraith gave invited lecture at Stanford University, Stanford, California. Topic: DAML-Enabled Semantic Web Services and Web Service Composition.

April 31, 2001. McIlraith gave presentation at the Second International Workshop on the Semantic Web (SemWeb'2001) at WWW-10 (World Wide Web Conference). Paper: ``Mobilizing the Web with DAML-Enabled Web Services"

March 22, 2001. Fikes gave PARC Forum presentations at Xerox Alto Research Center (PARC). Topic: "Steps Toward the Semantic Web: Putting Computer Interpretable Knowledge On Your Web Page"

Presentations at the DAML/Horus Meeting, Arlington, February 16, 2001.
30 minute introduction to Ontologies presented by Deborah McGuinness.
30 minute introduction to Web Services including an overview of KSL's DAML-Enabled Web Services Project presented by Sheila McIlraith.

Presentations at the DAML PI Meeting, Arlington, February 13-15, 2001.
Overview of KSL's Axiomatic Semantics for RDF, RDF-S, and DAML+OIL presented by Richard Fikes.
Overview of KSL's DAML effort presented by Deborah McGuinness.
Overview of KSL's DAML-Enabled Web Services Project presented by Sheila McIlraith.
Deborah McGuinness led the language breakout session on Feb 14, 2001.

February 8, 2001 – McGuinness presented Ontologies for Knowledge Environment work at NCAR – National Center for Atmospheric Research, Boulder, Colorado

January 11, 2001 McGuinness, McIlraith, Fikes met with Nancy Wheeler and Brian about DAML work migration to military applications.

December, 2000. McGuinness presented the Chimaera ontology evolution environment demonstration at the joint European Union/United States language meeting in Washington, DC.

October 4, 2000. McGuinness demonstrated the Chimaera ontology evolution environment to Daimler Chrysler representatives.

September 11-14, 2000. McGuinness was an invited teacher at the European Fall School. University of Freiburg, Germany. Course: Ontologies for the Web and Beyond.

August 16, 2000. McGuinness was an Invited speaker at ICCS 2000.   (publication: Deborah L. McGuinness. ``Conceptual Modeling for Distributed Ontology Environments,'' In the Proceedings of the Eighth International Conference on Conceptual Structures Logical, Linguistic, and Computational Issues (ICCS 2000), August 14-18, 2000, Darmstadt, Germany.)

August 14, 2000. McGuinness and McIlraith present KSL work at DAML Kickoff meeting. Boston, Mass.

August 2, 2000. McGuinness, Wilder, and Jenkins demonstrated Chimaera at the Intelligent Systems track of AAAI 2000. (publication: Deborah L. McGuinness, Richard Fikes, James Rice, and Steve Wilder, ``The Chimaera Ontology Environment,'' In the Proceedings of the Seventeenth National Conference on Artificial Intelligence (AAAI 2000), Austin, Texas, July 30 - August 3, 2000.)

August 2, 2000. McIlraith presented paper at AAAI 2000. Consultative, advisory, and collaborative functions with other laboratories and agencies

November 5-9, 2006. McGuinness attends International Semantic Web Conference and associated workshops on GeoSpatial Reasoning, User Interfaces, and Owl experiences and Directions in Athens, Georgia.

Summer and Fall 2006. McGuinness participates in NASA telecons and helps to plan the NASA semantic web roadmap.

January 18-19, 2006. McGuinness attends kickoff meeting for Intelligence community next generation Combine program to discuss trust and explanation in intelligence settings.

December 13, 2005. McGuinness meets with Greaves, Chaudhri, Porter (U. of Texas), Israel, (and others from SRI) to follow-up November meeting about semantic web programs Vulcan could fund as a potential way to leverage and extend the DAML program.

November 8, 2005. McGuinness meets with Mark Greaves (Vulcan (and past DAML program manager)) and Vinay Chaudhri (SRI) to discuss semantic web programs Vulcan might fund.

November 7, 2005. McGuinness attends DERI international meeting to discuss semantic web internationalization.

August 25, 2005. McGuinness meets with Hirsh and Borgida at Rutgers to discuss semantic web opportunities.

August 24, 2005. McGuinness visits MIT/W3C in Boston to discuss use of proof and trust work partially funded by DAML in W3C and NSF efforts.

July 13-14, 2005. McGuinness provides consulting to ISO 11179 and 19763 integration preparation for the XMDR Berkeley meeting on July 15, 2005.

July 10, 2005. McGuinness presents a tutorial on the semantic web with Mike Dean at the American Association for Artificial Intelligence National Meeting, Pittsburgh, PA.

June 21, 2005. McGuinness participates in DARPA learning by reading meeting in Seattle Washington at Noah Friedland's request.

June 7, 2005. McGuinness presents the Semantic Web and OWL at Oracle in Redwood shores, ca. and consults about integrating semantic web owl activities with Oracle led XML activities in W3C.

June 2005. McGuinness and Pinheiro da Silva host Li Ding, student of Finin at UMBC and integrate Swoogle and Inference web.

May 24, 2005. McGuinness and Fikes attend the Department of Homeland Security meeting on Text Analysis and brief on semantic web work that can be leveraged.

May 5-6 2005. McGuinness presents invited talk at the NSF Geon meeting – a meeting on Ontologies for Geologists and cyber-infrastructure for science. San Diego, CA.

April 27, 2005. McGuinness participates in W3C workshop in Washington DC supporting the Rules submission from the EU/US joint committee. (McGuinness was one of the submitters of the proposal.)

April 7, 2005. McGuinness gave plenary talk on the Semantic Web at the Darpa run Semantic Web for National Security Meeting. She also was one of 6 people asked to provide consulting hours for the government and attendees.

March 24, 2005. McGuinness participates in an the OMG meeting on Model Driven Architecture and Web Services giving an invited talk on the Semantic Web and participating in a panel on wed security, trust, and infrastructure to bridge the software engineering and semantic web communities. Orlando Florida.

March 17, 2005. McGuinness met with France Telecom concerning use of semantic web services in industry.

Feb 22-23, 2005. McGuinness gives invited briefing on DAML explanation and trust work at an Intelligence Community Technical Exchange meeting on Ontologies. Sierra Nevada Corporation. San Antonio, Texas.

August 4, 2004. McGuinness gives an invited talk on DAML explanation and trust work at the IBM New Paradigms in Using Computers Symposium, Almaden, Ca.

June 2004. McGuinness provides semantic web and OWL expertise to NGA. Onsite tutorial for August 2004.

May 2004. McGuinness attends face to face semantic web services initiative meeting co-located with the DAML PI meeting.

November 2003. McIlraith provides semantic Web services expertise to IBM TJ Watson.

October 2003. McIlraith completed transition of OWL-S and Web service compositin work to Sony

July – September 2003.   McGuinness participated in the DARPA jumpstart effort concerning ToDo requirements by program managers and academics for IPTO and KPAD.

July 2003. McGuinness provided a keynote talk at the Information Fusion Conference in Australia and met with DSTO (a DARPA like structure for Australia) and AFOSR for the Asian Pacific about Ontologies.

June 2003. McGuinness attended the Darpa evaluation of Cyc in Austin. McGuinness is on the 4 person executive council and is generating a review of Darpa's investment in Cyc.

April 2003 McGuinness and Fikes briefed ARDA, CIA, NSA on Inference Web and JTP and DQL.

April, 2003   Briefed Sentius on OWL and Semantic Web

Continuing. Consulting support for broadening the reach of DAML for use by Government contractors such as Cyladian.

Continuing. Support of Ultralog, RKF, AQUAINT, and NIMD projects usage of DAML.

October 2002. McGuinness presents Semantic Web for Cyberinfrastructure for NSF at the National Center for Atmospheric Research.

October 2002. McGuinness presents DAML and semantic web technology at GM Research center Detroit Michigan.

October 2002. McGuinness represents Stanford and DAML at W3C WebOnt meeting in Manchester England.

July 2002. McGuinness hosts W3C WebOnt meeting at Stanford.

March 27, 2002. Fikes and McGuinness met with John Prange from ARDA to discuss ontology technology.

February-March 2002, McIlraith represented DAML-S and Web Services on IXO study panel.

January – March 2002, McIlraith worked with Fortune 500 company to help integrate DAML-S and KSL-s Web service composition tool into our product.

February 8, 2002. McGuinness gave an invited talk on ontologies in Intel's Semantic web day. Other invited speakers were Hendler and Berners-Lee.

February 4, 2002. McGuinness organized Stanford's participation in a follow-up meeting to the NIMD meeting. Participation on Stanford included Fikes, McIlraith, McGuinness. Outside participation included DIA, PNNL, and NSA. The goal was to reuse ontology technology in government projects.

January 14-15. McGuinness participated in the first face to face meeting of the W3C Web Ontology working group. McGuinness ran the requirements subgroup meeting.

January 7-9, 2002. McGuinness was an invited participant in the Novel Intelligence for Massive Data meeting in Washington DC and helped lead the knowledge representation breakout group.

December 2001. McGuinness participated as invited member of the DARPA Information Fusion workshop. Captiva Island, Florida

November 2, 2001. McGuinness met with Bernard Burg HP about use of DAML for Agent Cities and other related semantic web projects.

Multiple visits Fall, 2001. McIlraith met with Plutowski from Sony Research Labs, San Jose to discuss Sony's use of DAML-S and Golog-based agent technology for Web service composition.

October 25, 2001. McGuinness met with members of Xerox Parc including Bobrow about use of DAML in Xerox projects.

October 3-5, 2001. McGuinness participated as invited member of EU/NSF workshop on the future of the Semantic web, W3C Sophia-Antipolis, France.

September 28, 2001– Fikes, McGuinness, and McIlraith met with Nado, Wong and others from Cisco Systems, Mountainview, CA. concerning the use of DAML-S for CISCO Web service markup.

September 2001 – Produced quad chart and FY01 reports for DAML.

September 7, 2001 – McGuinness met with Elbaz from Applied Semantics about possible use of markup languages for enhanced web search.

August 27, 2001 – Fikes, McGuinness, and McIlraith met with Cisco systems about potential use of markup languages for the meta description format project.

August 14, 2001 – McGuinness met with Decision Direct Institute to discuss the use of the semantic web for support of international agricultural knowledge applications.

August 5, 2001 – McGuinness attended the American Association for Artificial Intelligence meeting for executive councilors.

August 1-3, 2001 – McGuinness co-chaired the International Description Logic Workshop at Stanford.

August 1, 2001 – McGuinness co-founded the semantic web foundation along with other co-organizers of the international semantic web working symposium.

July 30-August 1- McGuinness co-organized the Semantic Web Working Symposium at Stanford and co-facilitated the Ontology track of the workshop.

 July 30, 2001 -- McIlraith and Hendler co-facilitated 2 day session on ``Web Applications and Web Services''
July 17, 2001 – McGuinness co-organized and met with the EU/US Joint committee on markup languages.

July, 2001 – McIlraith met with members of the European IBROW group to discuss the use of DAML-S for FIPA and IBROW.

July, 2001 -- Fikes and McIlraith, met with Nado, Wong and others from Cisco Systems, Mountainview, CA. concerning the use of DAML-S for CISCO Web service markup.

May, 2001 – McIlraith met with members of the Stanford Medical Informatics (SMI) group to discuss the use of Protégé for Web services editing.

May, 2001 – McIlraith met with North American members of the IBROW team to discuss the use of KSL's Web service composition tool for IBROW applications.

May, 2001 – McIlraith met with European and North American members of the Agent Cities initiative concerning the use of DAML-S and Web services for the Agent Cities program.

May 9, 2001 – McGuinness met with Boi Faltings (sabbatical at Stanford from Switzerland) and Jonathon Dale – Fujitsu about DAML use in a US Agent Cities effort.

May 1, 2001 – McIlraith met with Goble and associates from Manchester University concerning the use of OILEd for Web services editing.

April 31, 2001 – McIlraith met with members of IBM Emerging Technologies Group concerning Web services and the integration of DAML-S with IBM's Web services activities.

April 17 – McGuinness met with Joe Caroli on DAML work at Stanford.

April 11-12 – McGuinness met with Hendler and Tom Martin about the semantic web for the military. McGuinness briefed the Naval War College on Ontologies. This led to the series run by DAML on the semantic web for the military.

March, 2001 – Fikes, McGuinness and McIlraith met with Bob Nado, Shirley Wong and associates from Cisco Systems concerning the use of DAML-S and DAML-enabled Web Services at Cisco.

March, 2001 – McIlraith met with Ora Lassila from Nokia concerning Web services.

February, 2001 – McIlraith co-initiated DAML-S Coalition with Hobbs, Martin, Natarayan (SRI), Payne, Sycara (CMU), Burstein (BBN).

February 8, 2001 – McGuinness briefed the National Center for Atmospheric Research on Ontology environments and the DAML program. This was integrated into a proposal to provide a knowledge environment for the GeoSciences.

January 12, 2001 – McGuinness met with Goble (Manchester) about DAML integration with FACT and the GONG medical projects. Subsequently set up subcontract with Manchester for DAML.
January 11, 2001 – Fikes, McGuinness, and McIlraith met with Nancy Wheeler and Brian Bennett concerning the use of DAML in Intelink,.

December, 2000 – McGuinness attended the joint European Union/ US ontology language working group meeting in Washington, DC.

November 10, 2000 - McGuinness and McIlraith meet with Cheyer (VerticalNet), Lassila (Nokia), and SRI representatives to discuss services related needs from DAML.   McGuinness also met on November 10 with Lassila concerning DAML translator issues along with general ontology tools issues and rule language extension needs for wireless devices, among other things.

3 meetings. September – December, 2000.. McIlraith met with the SRI DAML team to discuss DAML Web services, and the possibility for future collaboration.

1 meeting. September – December, 2000. McIlraith met with Stefan Decker from the other Stanford DAML team to discuss KSL's services work and to discuss opportunities for future collaboration.

September 19, 2000. McGuinness coordinated semantic web language meeting between DAML representatives and European OIL community. Amsterdam, Netherlands. Attendance: Fensel, van Harmelan, Horrocks, Staab, etc.

September 19, 2000. McGuinness gave invited talk at the Free University of Amsterdam. Talk: Ontology Environments.

August 31 and September 1, 2000. Fikes, McGuinness, and McIlraith met with Mike Dean and Joe Rockmore to discuss KSL's DAML project, DAML support tasks for BBN, and how KSL's DAML project might be used by DARPA.

August 30, 2000. McGuinness met with Carole Goble – Information Technology Director of Manchester University concerning reasoners and ontology environments.

August 17, 2000. McGuinness met with description logic community (at the international DL workshop) on DAML-ONT and DLP (Lucent Bell Laboratories), FACT (Manchester University), etc. Aachen, Germany.

August 1-2, 2000. McGuinness met with Hendler (DARPA) and Burke (DARPA) concerning ontology tools.

July 19-20, 2000. McGuinness met with W3C representatives (Berners-Lee, Connolly, Lassila) and other DAML invitees on DAML language jumpstart meeting. Presentation by McGuinness on Stanford ontology tools and commercial ontology interests.

June, 2000. McIlraith met with colleagues at SRI to discuss DAML Web Services.

New discoveries, inventions or patent disclosures   none